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Reducing resin content and board density without adversely affecting the mechanical properties of particleboard through controlling particle size

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Abstract: Density and resin content are two factors that have a significant effect on the production cost of wood composite. However, particle size affects resin content and density, which suggests that the interaction of these three factors can be manipulated to reduce the board density and resin content of particleboard without adversely influencing its mechanical properties. Some mathematical functional forms based on resin content, board density and slenderness ratio were regressed and an appropriate form was chosen. According to analysis of the results using SHAZAM 9 software, the exponential function best fit the experimental data. Finally, "indifference curves" of mechanical properties were illustrated and analyzed. The results indicated that negative effects of density or resin content reduction on mechanical properties could be compensated for by controlling particles' slenderness ratio. Interestingly, increases in slenderness ratio compensated for the negative effects of decreases in resin content or board density on module of rupture (MOR) and module of elasticity (MOE). Moreover, this "compensation ratio" intensified as resin content or density decreased and/or as the MOR or MOE increased. On the other hand, reduction in slenderness ratio indicated a complementary effect on reducing internal bond (IB) strength, a result of decreases in resin content or density. Moreover, this "complementary ratio" was intensified as resin content or density decreased and/or as IB strength increased.

Keywords: mechanical properties; board density; resin content; slenderness ratio; particleboard.

Introduction

Resin content and board density have a direct impact on the properties of particleboard. This assumes significance in light of the fact that the particleboard industry is facing two important concerns. A shortage of wood particles, combined with the need to reduce costs and toxicity by reducing the consumption of resin, is forcing a reexamination of particleboard construction.

There is a high correlation between density and mechanical properties of boards: as board density increases, mechanical properties improve (Maloney 1977; Wong et al. 1999; Mendes et al. 2008). While higher density improves particleboard quality, it may not be a feasible way to improve the mechanical properties of particleboard: forest resources are decreasing, and particleboard manufacturers must compete for wood supplies with other industries (particularly medium-density fiberboard and pulp and paper).

Urea-formaldehyde (UF) is the most important adhesive for composite wood products, playing a very important role in the manufacture and production cost of particleboard. Although resin only makes up about 10% of particleboard by weight, its cost comprises more than 30% of the total cost of production (Amiri 1998). This suggests that reducing resin content may result in a significant decrease in total particleboard production cost. In addition, the formaldehyde released during production and use of wood-based composites is carcinogenic (Prasittisopin and Li 2010). This has given rise to widespread complaints about the bad odors and adverse health effects associated with formaldehyde emissions from wood-based composites (Wang et al. 2007; Kazakevics and Spedding 2009).The emission of formaldehyde from particleboard decreases as the ratio of formaldehyde to urea decreases. However, this also negatively affects the physical and mechanical properties of the particleboard (Que et al. 2007).

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Most studies in this area have focused on resin efficiency, including examinations of the surface of wood particles and resin efficiency (Hill and Wilson 1978) and measuring resin-adhesive spray characteristics (Zhang et al. 2009), but there were few studies that have directly investigated the possibility of reducing board density and resin content without adversely influencing the board's properties. Particle size is one of the factors that can be manipulated to improve the physical and mechanical properties of particleboard. Increasing the length of particles and the slenderness ratio (length: thickness) also increases the module of rupture (MOR) and module of elasticity (MOE) (Post 1958; Barns' 2001; Mara 1992), but decreases internal bond (Sun & Arima 1999; Miyamoto et al. 2002). Particle size affects macro-voids in particleboard. Sacky and Smith (2010) reported that macro-voids increased with increasing strand thickness, but decreased with increasing strand length and width. Sackey et al. (2008) improved the core bonding strength of particleboard by replacing fine particles with coarse particles in board cores.

These results suggest that improving particle size can compensate for the negative effect of decreasing resin content and board density on the physical and mechanical properties of particleboard. This study explored options for varying particle size to reduce board density and resin content, and as a result decreasing both formaldehyde emissions and cost without adversely influencing the board's mechanical properties.

Materials and methods

Board fabrication

Wood blocks of poplars were ground with a laboratory Hammer mill. Particles were dried to a moisture content of less than 3%. After drying, the particles were sifted by passing through three hand-held screens including 5, 8 and 12 meshes (Fig.1). The length, width and thickness of 5 g screened particles were measured for each mesh (+5, -5 +8, -8 +12 and -12) with a micrometer caliper. Average dimensions of classified particles are shown in Table 1. Urea formaldehyde (solid content of 55%) was used as an adhesive. Pressures of 35 $kg{\cdot}cm^{-2}$ at 180±2 ºC for 5 min were applied for mat formation. Finally, 108 single-layer particleboards with three levels of density (0.65, 0.7 and 0.75), three levels of percentage of adhesive (8, 9.5, and 11%) and four levels of particle size (+5, -5 +8, -8 +12 and -12) were manufactured in the laboratory. For moisture conditioning, the boards were kept at 65 ± 5% relative humidity at 20 ± 2ºC for two weeks.

Experiments

MOE, MOR and IB strength samples were cut according to the EN 310 and 319 standards respectively. Then the samples were tested by INSTRON 4489.

Modeling

Three kinds of modeling (linear, exponential and quadratic equation) were performed using SHAZAM9 software. The accuracy of these models was studied using Equation 1.

$$\% MAE = \frac{1}{n}\sum_{i=1}^{n} \left| \frac{z(x_i) - z(x_j)}{z(x_i)} \right| \times 100 \tag{1}$$

where MAE is the average absolute error percent, n is the number of observations, $Z(x_i)$ is the experimental value, and the $Z(x_j)$ is the predicted value.

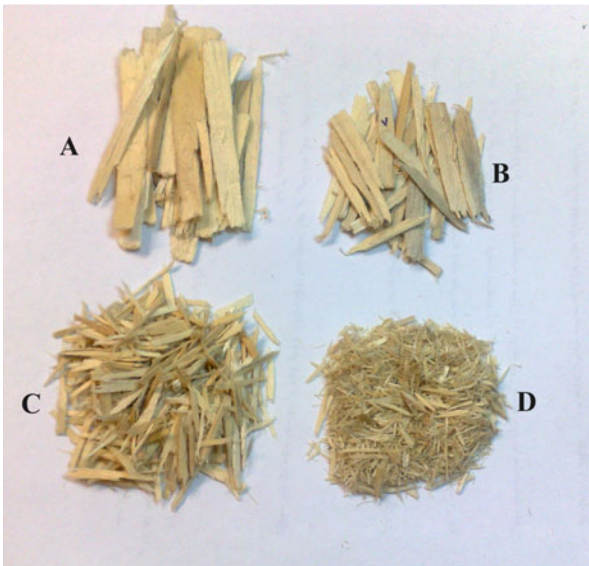

Fig.1 Four types of particles A, +5 mesh; B, -5 + 8 mesh; C, -8 +12; D, -12 mesh

Table 1. The features of particles for each mesh

Mesh	Length (mm)	Width (mm)	Thickness (mm)	L/W	L/T	W/T
A (+5)	55.1 (7.7) *	7.9 (3.5)	1.19 (0.3)	6.97	46.30	5.85
B (-5+8)	28.4 (3.1)	4.7 (1.3)	0.84 (0.1)	6.05	33.70	5.57
C (-8+12)	13.98 (3.8)	2.18 (0.4)	0.65 (0.2)	6.41	21.51	3.35
D (+12)	3.98 (2.3)	0.82 (0.2)	0.31 (0.1)	4.85	12.84	2.65

* The value into parenthesis represents Standard deviation.

Results and discussion

Modeling techniques are useful for optimizing the production costs and properties of particleboard. Three kinds of function (linear, quadratic and exponential) were obtained using SHAZAM 9 software. The quadratic function parameters were not significant according to the software results (P-value). MOR, MOE and IB were predicted by linear equations (Equations 2, 4, and 6 respectively) and exponential equations (Equations 3, 5, and 7 respectively).

$$MOR = 61D + 0.54851G + 0.14082L/t - 34.283 \tag{2}$$

$$MOR = (d)^{2.4892}.(G)^{0..3165}.(\frac{L}{t})^{0.20578}.e^{2.3656} \quad (3)$$

$$MOE = 6377.6D + 71.94G + 18.572L/t - 388 \quad (4)$$

$$MOE = (d)^{2.6809}.(G)^{0.41046}.(\frac{L}{t})^{0.27956}.(e)^{6.6005} \quad (5)$$

$$IB = 0.6924D + 0.034079G - 0.0022851L/t - 0.31083 \quad (6)$$

$$IB = (D)^{1.1843}.(G)^{0.75245}.(\frac{L}{t})^{-0.12489}.e^{-1.7228} \quad (7)$$

where L and t are length and thickness of particles respectively, and *D, G, MOR, MOE,* and *IB* are density, resin content, module of rupture, module of elasticity, and internal bond of particleboard, respectively.

Average percent errors for MOR, MOE, and IB obtained based on Equation 1 showed that an exponential function can predict MOR, MOE, and IB with less error than a linear function (Table 2). Therefore, exponential functions were rewritten for each mechanical property as follows:

$$(\frac{L}{t}^{0.20578})^{\frac{1}{0.20587}} = (MOR/D^{2.4892}.G^{0.3165}.e^{2.3656})^{\frac{1}{0.20587}} \quad (8)$$

$$(\frac{L}{t}^{0.27956})^{\frac{1}{0.27956}} = (MOE/D^{2.6809}.G^{0.41046}.e^{6.6005})^{\frac{1}{0.27956}} \quad (9)$$

$$(\frac{L}{t}^{-0.12489})^{\frac{1}{-0.12489}} = (IB/D^{1.1843}.G^{0.75245}.e^{-1.7228})^{\frac{1}{-0.12489}} \quad (10)$$

Equations 8, 9, and 10 were used for drawing the indifference curves for MOE (1400, 1600, 1800, 2000, and 2200 MPa), MOR (14, 16, 18, 20, and 22 MPa), and IB (0.35, 0.4, 0.45, and 0.5 MPa). The relationships between resin content and slenderness ratio under a constant density ($0.7 g·cm^{-3}$), and between density and slenderness ratio under a resin constant (9.5%) were investigated.

Table 2. Average error percent of mechanical properties

Mechanical properties	Average error percent	
	Exponential function	Linear function
MOR	14.82	18.13
MOE	10.13	16.9
IB	19.17	35.6

MOR

Resin content

The results showed that there is a substitution relationship between resin and slenderness ratio, in which it is possible to maintain a constant value for MOR by adding slenderness ratio, even as resin content is reduced. This substitution has two main characteristics. First, for higher values of MOR, the resin reduction needs more units of slenderness ratio than for lower values of MOR. For example, when MOR is in the low level (14 MPa), decreases in resin content from 11% to 9.5% and then to 8% could be compensated for by adding only two and three units of slenderness ratio respectively; however, for higher value of MOR (22MPa), decreases in resin content from 11% to 9.5% and then to 8% could be compensated for by adding 16 and 24 units of slenderness ratio respectively (Table 3). Second, under a constant MOR, decreases in resin content must be compensated by greater proportional increases in slenderness ratio to keep MOR constant (Table 3). In conclusion, the higher the MOR value and the lower the resin content, the greater becomes the substitution ratio between slenderness ratio and resin content. Fig 2 illustrates the effects of changes in slenderness ratio with different MOR and resin content on MOR indifference curves.

Table 3. The value of slenderness ratio that maintains a constant MOR strength with decreasing resin content under a constant density ($0.7 g·cm^{-3}$)

Decrease in resin content (%)	MOR					
	14	16	18	20	22	Average
11–9.5	2	3	6	10	16	7.44
9.5–8	3	5	9	15	24	11.14

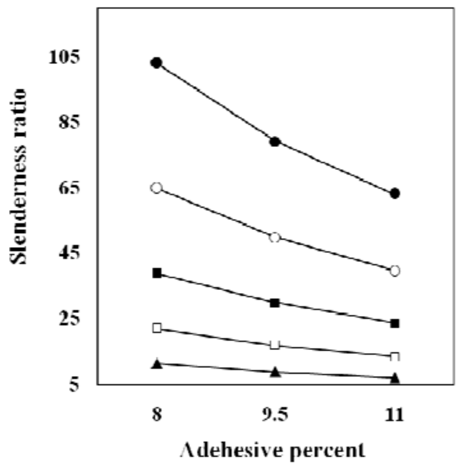

Fig. 2 MOR indifference curves under a constant density ($0.7 gcm^{-3}$); MOR=14▲, MOR=16□, MOR=18■, MOR=20○, MOR=22●)

Density

Slenderness ratio and board density showed a positive relationship with MOR: when each of these variables increased, MOR increased (Post 1958; Maloney 1977). This suggests that the negative effects of decreasing board density on MOR could be compensated for by an increase in slenderness ratio. The results showed that for the lowest value of MOR (14MPa), a decrease in density from $0.75 g·cm^{-3}$ to $0.7 g·cm^{-3}$ could be compensated for

by adding 3.97 units of slenderness ratio. A further decrease to 0.65 g·cm^{-3} could be compensated for by adding 10.18 units of slenderness ratio. Increasing MOR from 14 MPa to 22 MPa increased the substitution ratio between density and slenderness ratio (Table 4). Therefore with increasing MOR and decreasing density the substitution ratio between density and slenderness ratio increased (Fig. 3).

Table 4. The value of slenderness ratio that maintains a constant MOR strength with decreasing density under a constant resin content (9.5%)

Decrease in density (g/cm^3)	MOR					
	14	16	18	20	22	Average
0.75 - 0.7	3.97	7.60	13.46	22.46	35.70	16.64
0.70 - 0.65	10.18	19.47	34.51	57.59	91.52	42.65

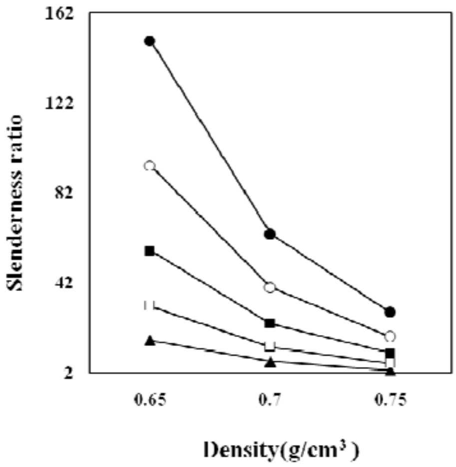

Fig. 3 MOR indifference curves under a constant resin content (%); (MOR=14▲, MOR=16□, MOR=18■, MOR=20○, MOR=22●)

MOE

Resin content

Slenderness ratio and resin content have a direct impact on MOE: increasing either of them leads to increased MOE in the particleboard (Post 1958; Maloney 1977). This suggests that the negative effects of decreasing resin content on MOE could be compensated for by an increased slenderness ratio. For the lowest value of MOE (1400 MPa), decreasing resin content from 11% to 9.5% and then to 8% could be compensated for by adding 2.14 and 3.17 units of slenderness ratio respectively. For the highest value of MOE (2200 MPa), the substitution ratio between slenderness ratio and resin content increased (Table 5): for a decrease in resin content from 11% to 9.5% and then to 8%, the slenderness ratio should be increased 10.78 and 15.98 units respectively. Therefore, the results indicated there is an increase in slenderness ratio when resin content is decreased and MOE increased (Fig. 4).

Table 5. The value of slenderness ratio that maintain a constant MOE strength with decreasing resin content under a constant density (0.7 g cm^{-3}).

Decrease in resin content (%)	MOE					
	1400	1600	1800	2000	2200	Average
11 - 9.5	2.14	3.45	5.26	7.67	10.78	5.86
9.5 - 8	3.17	5.11	7.79	11.36	15.98	8.68

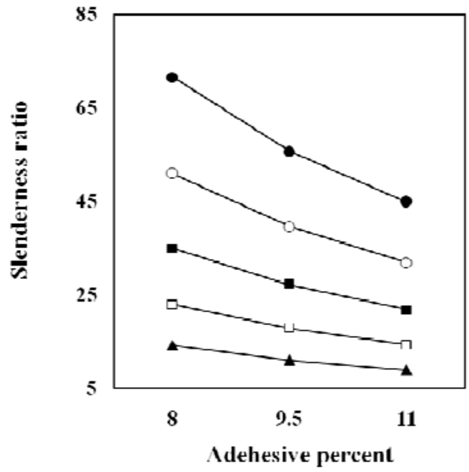

Fig. 4 MOE indifference curves under a constant density (0.7 gcm^{-3}); (MOE=14▲, MOE=16□, MOE=18■, MOE=20○, MOE=22●)

Density

Increases in slenderness ratio differed depending on MOR value and board density. With reduced board density, higher values of MOE were compensated for with increases in the slenderness ratio to keep a constant MOE. The results showed that for the lowest value of MOE (14MPa), a decrease in density from 0.75 to 0.7 g·cm^{-3} could be compensated for by adding 6.88 units of slenderness ratio. But as density decreased, the substitution ratio of density with slenderness ratio increased: decreasing density from 0.7 to 0.65 g·cm^{-3} could be compensated for by adding 14.73 units of slenderness ratio. Also, increasing MOE from 1400 to 2200 MPa increased the substitution ratio of density with slenderness ratio (Table 6). Fig. 5 shows the change of substitution ratio for slenderness ratio and board density to maintain a constant MOE.

Table 6. The value of slenderness ratio that maintains a constant MOE strength with decreasing density under a constant resin content (9.5%)

Decrease in density (g/cm^3)	MOE					
	1400	1600	1800	2000	2200	Average
0.75 - 0.7	6.88	11.10	16.92	24.66	34.68	18.85
0.70 - 0.65	14.73	23.75	36.19	52.75	74.18	40.32

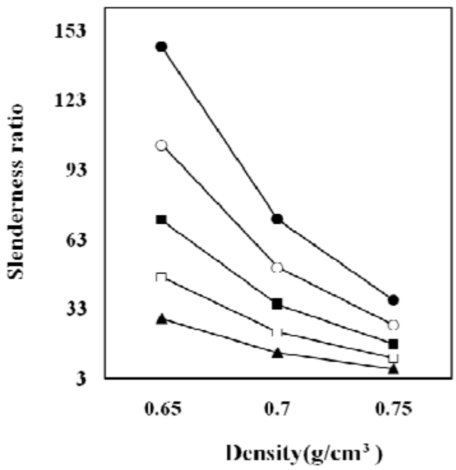

Fig. 5 MOE indifference curves under a constant resin content (9.5%); (MOE=14▲, MOE=16□, MOE=18■, MOE=20○, MOE=22●)

Particle slenderness ratio, resin content and board density have a positive relationship with MOR (Maloney 1977; Mara, 1992; Barnse 2001) In other words, with decreasing resin content and density; the slenderness ratio should be increased to keep MOE and MOR constant. On the other hand, the effects of increasing the particle surface area on the bending strength of particle-based product are very crucial (Mara 1992), as larger particles provide a sufficiently large contact area between particles (Barnse 2001). Moreover, with the same applied resin content, large particles receive more resin than small particles (Sun and Arima 1999). This suggests that increasing particle size may make it possible to reduce board density, resin content and especially formaldehyde emission without decreasing bonding strength.

IB

Resin content

Several studies have shown that increasing slenderness ratio has a negative effect on IB strength of particleboard: in other words, when it increases, the IB strength decreases (Maloney 1977; Miyamoto et al., 2002). In contrast, resin content has a positive effect on IB strength. In the case of IB strength, reduced resin content could be compensated for with a decrease in slenderness ratio. Although decreases in slenderness ratio have a negative effect on bending strength, higher values of IB strength do not need to decrease slenderness ratio considerably. For example, for the highest value of IB (0.5MPa), a decrease in resin content from 11% to 9.5% and then to 8% can be compensated for by reducing the slenderness ratio by 9.58 and 4.48 units respectively (Table 7). Also with a decrease in resin content, the compensation ratio between reductions in resin and slenderness ratio increased. Overall, results indicated that for higher IB and lower resin content, the complementary values of resin content and slenderness ratio decreased (Fig. 6).

Table 7. The value of slenderness ratio that maintains a constant IB strength with decreasing resin content under a constant density (0.7 g·cm^{-3})

Decrease in resin content (%)	IB				
	0.35	0.4	0.45	0.5	Average
11 - 9.5	171.27	58.79	22.90	9.85	65.70
9.5 - 8	77.85	26.72	10.41	4.48	29.86

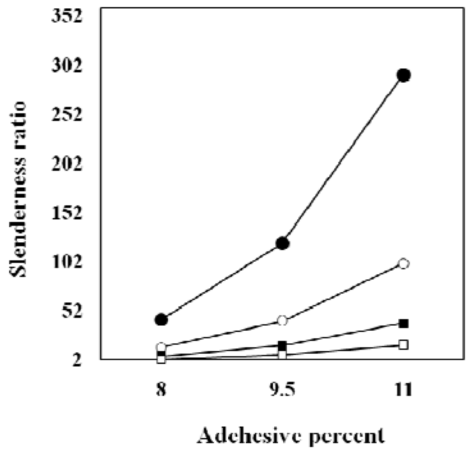

Fig. 6 IB indifference curves under a constant density (0.7 g·cm^{-3}); (IB=0.35●, IB=0.4○, IB=0.45■, IB=0.5□)

Density

The effects of slenderness ratio and board density on IB strength are not the same. IB strength increased with increasing board density (Maloney 1977; Wong et al., 1999; Miyamoto et al., 2002) while it decreased with an increase in slenderness ratio. Thus, the negative effect of decrease in board density should be compensated for with a decrease in slenderness ratio to keep IB strength constant. The results showed that for the lowest IB strength (0.35MPa), decreasing density from 0.75 g·cm^{-3} to 0.7 gcm^{-3} and then to 0.65 g·cm^{-3} could be compensated for by reducing the slenderness ratio by 80.1 and 30.2 units respectively to keep IB strength constant. But with increasing IB strength, the substitution ratio of density and slenderness ratio decreased: at the highest value of IB strength (0.5MPa), decreasing density from 0.75g·cm^{-3} to 0.7g·cm^{-3} and then to 0.65g·cm^{-3} could be compensated for by reducing the slenderness ratio by 4.6 and 1.76 units respectively (Table 8). Overall, results indicated that for higher IB and lower density, the complementary value of density and slenderness ratio decreased (Fig. 7). Increasing density leads to increased IB strength because it provides better inter-particle contacts under compression (Sacky et al. 2008). However, thicker and shorter particles have a higher specific surface area, and they receive more resin and provide better inter-particle contacts than thinner and higher particles under the same applied resin and density.

Table 8. The value of slenderness ratio that maintains a constant IB strength with decreasing density under a constant resin content (9.5%)

Decrease in density (g·cm^{-3})	IB				
	0.35	0.4	0.45	0.5	Average
0.75–0.7	80.10	27.50	10.71	4.61	30.73
0.7–0.65	30.28	10.39	4.05	1.74	11.62

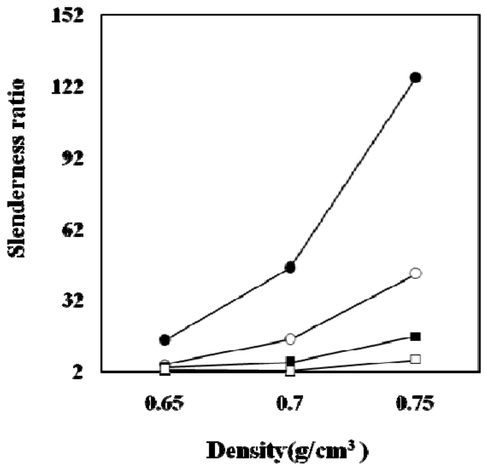

Fig. 7 IB indifference curves under a constant resin content (9.5%); (IB=0.35●, IB=0.4○, IB=0.45■, IB=0.5□)

Conclusion

The conclusions based on the conditions of this study are:

(1) Reducing consumption of raw material (in other words, reducing resin content and density) could be compensated for by optimizing particle size without adversely affecting the mechanical properties of particleboard.

(2) Density, resin content, and slenderness ratio indicated a positive relationship for both MOE and MOR, suggesting that reducing density and resin content could be compensated for by increasing particle size to maintain constant MOE and MOR strength. Increases in MOE and MOR and decreases in resin content and density led to increases in the substitution rate between slenderness ratio and both density and resin content.

(3) IB strength decreased with increasing slenderness ratio and increased with increasing density and resin content, suggesting that the density, resin content and slenderness ratio have complementary effects on the mechanical properties. Increasing IB strength and reducing density and resin content led to decreases the values of supplementation for density and resin content with slenderness ratio.

(4) Reducing resin content and board density can produce significant savings in particleboard production costs. In addition, reducing resin content can lead to decreased formaldehyde emissions from the boards and improve the health and safety of workers and consumers.

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